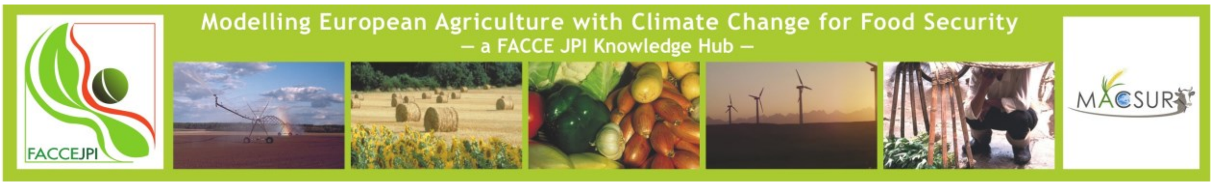

FACCE MACSUR

Report on Task H1-XC1 - Sub-task XC1.1.

'Needs on model improvement'

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Abstract

The need to answer new scientific questions can be satisfied by an increased knowledge of physiological mechanisms which, in turn, can be used for improving the accuracy of simulations of process-based models. In this context, this report highlights areas that need to be further improved to facilitate the operational use of simulation models. It describes missing approaches within simulation models which, if implemented, would likely improve the representation of the dynamics of processes underlying different compartments of crop and grassland systems (e.g. plant growth and development, yield production, GHG emissions), as well as of the livestock production systems.

The following rationale has been used in the organization of this report. We first briefly introduced the need to improve the reliability of existing models. Then, we indicated climate change and its influence on the global carbon balance as the main issue to be addressed by existing crop and grassland (section 2), and livestock (section 3) models. In section 2, among the major aspects that if implemented may reduce the uncertainty inherent to model outputs, we suggested: i) quantifying the effects of climate extremes on biological systems; ii) modelling of multi-species sward; iii) coupling of pest and disease sub-models; iv) improvement of the carry-over effect. In section 3, as the most important aspects to consider in livestock models we indicated: i) impacts and dynamics of pathogens and disease; ii) heat stress effects on livestock; iii) effects on grassland productivity and nutritional values; iv) improvement of GHG emissions dynamics.

In Section 4, remarks are made concerning the need to implement the suggested aspects into the existing models.

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1. Introduction

The Task H1-XC1 ('Model comparison and improvement') of the second phase of MACSUR project was triggered by the need to answer new scientific questions and, at the same time, to improve the accuracy of simulations. In fact, as in an iterative process, the emergence of new questions can be satisfied by an increased knowledge of physiological mechanisms which, in turn, can be used for improving the reliability of the existing models. For increasing the model reliability it is therefore needed to investigate on the views and priorities of stakeholders (e.g. farmers, business men, decision makers, experimentalists) in order to have a general overview on the quality of performance of the models used in agriculture. In MACSUR, they include simulation models of arable crops, grasslands and livestock. Trade models are also present in MACSUR but are not dealt with in this report.

In this context, the sub-task XC1.1 'Survey on model improvement' focussed on increasing awareness on strengths and weaknesses associated with the use of state-of-the art aforementioned model types. Based on the modelling practice accumulated within MACSUR (and with linking to other experiences), this report highlights areas that need to be further improved to facilitate the operational use of simulation models. It describes missing approaches within simulation models which, if implemented, would likely improve the representation of the dynamics of processes underlying different compartments of crop and grassland systems (e.g. plant growth and development, yield production, GHG emissions) as well as livestock.

2. Description of the missing processes: crop and grassland models

Simultaneously with the evidence provided about climate change impacts on agriculture, the development, improvement and use of process-based models of crop and grassland systems have widely increased (e.g. Donatelli et al., 2002; Tubiello and Ewert, 2002; van Ittersum et al., 2003; Challinor et al., 2009a; White et al., 2011; Rötter et al., 2012a; Angulo et al., 2013; Boote et al., 2013). At present, several models characterized by a different degree of complexity are used to assess the impacts of climate change in agriculture and cope with the consequences of altered weather patterns.

Over the years, advancement in models has mostly been driven by the need to address issues (and develop applications) at larger scales than merely plot or field-sized areas, while considering multi-crop systems with daily (or sub-daily) time steps. In that, the introduction of decision rules was required to enhance the representation of management options, along with improving approaches to plant physiology and soil-plant-atmosphere interactions. More recently yet, to better understand the effects of climate change on agricultural systems, modelling studies have dealt with the uncertainties inherent to models (Rivington et al., 2006). This has prompted multi-model ensemble simulations (Palosuo et al., 2011; Rötter et al., 2012b; Asseng et al., 2013) and up-scaling approaches (Ewert et al., 2011), while also accounting for adaptation options (Howden et al., 2007; Moriondo et al., 2010a; Lobell et al., 2011b). With the global carbon balance becoming an issue, modelling efforts have been required to improve the mechanistic representation of plant responses to CO_2 (Tubiello and Ewert, 2002). Other issues have also received attention, which include: embedment of carry-over effects (Reckling et al., 2016), coupling of crop models to pest and disease sub-models, and a better formalization of the impact of extreme events (Challinor et al., 2005; Asseng et al., 2011; Moriondo et al., 2011; Eitzinger et al., 2013; Lobell et al., 2013; Tao and Zhang, 2013; Teixeira et al., 2013; Mariorano et al., 2014).

However, there are aspects that remain unresolved in the existing models, which contribute to the uncertainty inherent to model outputs. Below are reported some important gaps that have been identified.

2.1. *Climate extremes*

Changes in mean climate conditions and more frequent extremes imply widening the gap between food demand and crop production. Whilst changes in mean climate conditions can lead to a slow evolution of natural and managed ecosystems, so that possible adjustments can be anticipated, changes in weather extremes will may result in extended ecological and economic damages for which strategies for adaptation are not easy to find because they would take place under conditions of uncertainty because of the sparse and uneven distribution of such events. Therefore, if quantifying the effects of these extremes on biological systems is not straightforward by itself, still more complicated it is to reproduce and implement such effects into crop simulations.

Climate extremes need to be defined before accounting for them into simulation models. The lack of a unique definition makes indeed difficult to describe mathematically the effects of climate extremes. Currently, it is generally accepted as extreme an event whose occurrence exceeds a pre-determined threshold (i.e. low or a high percentile) resulting in a strong impact on society and/or biophysical systems (Kipling et al., 2016). Based on this general (statistically-based) definition, more specific definitions can be elaborated. For instance, as reported by Hanson et al. (2007), following the definition provided by the project Modelling the Impact of Climate Extremes (MICE), three types of extremes may be detected: a) diagnostic measures (e.g. number of days per year above the 95th percentile of temperature); b) impact-related measures (e.g. date of the first autumn frost); c) indices for the calculation of extreme value parameters based on distributions (e.g. the highest and lowest temperature values in each year, the highest daily rainfall amount in each year). Once defined, such indices may be coupled with eco-physiology characteristics of various crops, thus reproducing the behavior of a crop depending on the type of stress endured.

Despite simulation models have been improved over time, until to reach quite good predictions of the impacts of changes in average climate conditions, the reproduction of impacts of extreme events still remains a complex issue. So it is because the simultaneous occurrence of different extremes can generate complex physiological responses, depending on soil conditions, vegetation types and genotypic sensitivity. Also, the development of robust modelling approaches accounting for the combined effect of multiple stressors is often not supported by carefully designed experiments generating sufficiently detailed data for model calibration and validation under extreme conditions. For a comprehensive understanding of the impact of extreme events on grassland and crop systems, accurate information is required about soil and plant dynamics over gradients of management.

On these basis, there are needs in modelling related to: 1) the development of functions of how soil dynamics and plant physiological processes such as photosynthesis, respiration, transpiration, and biomass partitioning in plants are affected by extreme events; 2) the link between these functions and the system dynamics represented in existing modelled; 3) the implementation of specific physiological processes not yet represented (e.g. mobilization of sugar reserves to recover or to cope with these extremes).

2.2. *Modelling multi-species sward*

Grassland systems are typically multi-species systems. Simulation models usually design grasslands as simple mixes such as clover and ryegrass (i.e. DayCent, DNDC) (Lazzarotto et al., 2009). This simplification, however, limits our capabilities to reproduce the impacts of changing conditions of climate and management. Moreover, representing explicitly the species competition for resources would improve our capability to simulated forage quality and quantity, for instance to support studies on high protein forages in livestock systems. This is a promising option to reduce the use of supplementary feeds and nitrogen inputs (Lüscher et al., 2014; Suter et al., 2015), and its potential benefits for farm economy and environment could be assessed with dedicated models. Moreover, new model capabilities for simulations on multispecies swards would improve the analysis of grassland responses to changed climate conditions beyond the estimate of average grassland outputs (e.g. GHG emissions, aboveground biomass nitrogen leaching) for which the detailed representation of mixes is not required. At the same time, this would help developing suitable adaptation strategies.

Currently, only a few models are able to assess and reproduce the response of more species in a sward. This is the case of GEMINI (Soussana et al., 2012) but also of INTERCOM (Schippers and Kropff, 2001). With these approach, plants are well defined and described by biophysical parameters that can be directly measured or estimated. This makes it possible to simulate the plasticity of traits related to the morphology and physiology of plants and to the interaction between neighboring plants (Maire et al., 2013). Although strictly adherent to the underlying system, these models are complex and difficult to initialize and parameterize. In fact, they are often centered on the individual or defined at a sub-individual level, where competition between plants is represented in three dimensions. In addition, significant resources are needed to run the simulations in the case of large-scale studies on natural or managed grasslands. A model-by-species instance in the community is needed, which often leads to limiting the application of these models to simple communities of two or three species (Baumann et al., 2002; Corre-Hellouet al., 2009).

Extended datasets with characteristics of specific types of sward may be needed for developing processes to implement into simulation models (Confalonieri, 2014). Specific processes such as the potential biological N fixation in legumes or specific ecological requirements such as water needs, resistance to abiotic and biotic stresses and resilience may be further analyzed and translated into new equations. Also, modelling approaches which describe the changes in specie composition due to intra-species competition, presence of pathogens and micro-climatic conditions should be developed for a complete overview about the main factors affecting grassland composition. Accordingly, this would help finding optimized solutions in specific contexts, which may include suggesting the best composition for the conservation of landscape along the whole year, using the most suitable species to cope with exposure to climate events or the most resilient to fire in arid environment, etc.

2.3. Coupling of pest and disease sub-models

Climate not only identifies areas in which crops can find optimal conditions for growth and development, but also the range of conditions in which pathogens of specific crops are able to reproduce and develop. More specifically, thermal variables, levels of humidity and UV are usually identified as the most important variables (Chaparro et al, 2011; O'Connor et al, 2006; Stromberg, 1997; van Dijk et al, 2009) since their patterns describe the intra- and inter-annual spatial distributions, and the intensity of pathogens (Fox et al., 2011).

The expected changes in climatic conditions will likely drive distinct changes in the lifecycles of pathogens, thus affecting their vector capacity. These changes will mainly affect the relation between crop damages and the presence of pathogens through: i) the direct influence on the development, growth, survival, distribution and spread; ii) alteration of the host's physiology and defense; iii) changes of the relations among pathogens, hosts and competitors (i.e. natural enemies, competitors and mutualists).

However, climate change may not linearly affect the pathogens dynamics. Changes in thermal regimes can affect lifecycle of pathogens based on the adaptation capacity of the specie itself. For instance, despite mild winter temperature can reduce the mortality of specific pathogens, at the same time a decrease in snowpack cover may decrease the survival of those species which overwinter under the litter (Bale et al., 2002; Jamieson et al., 2012). Also, polyphagous species, living over several habitats at different latitudes and/or altitudes, will be likely less affected by climate changes compared to those monophagous.

The role played by pathogens over grassland systems is complex and not fully understood. Pathogens can affect swards in many ways mainly depending on the sensitivity of the plant species in the sward. Grassland composition can be modified and the type of composition or the productivity levels can strongly differ even if belonging to the same grassland typology. Pathogenic processes and their interactions with the environment are rarely considered by mechanistic models and particularly by grassland models. This aspect should be considered, however, also in consideration of the expected climate change. Considering pests and pathogens into mechanistic models firstly means to increase knowledge about their dynamics across different regions. This information should include fundamental aspects such as pathogens’ response to mean climate conditions and extremes, the role of antagonist species, and impacts on specific grassland composition, thus creating a useful database to build process models for inclusion in system models.

On these bases, several modelling needs can be identified. They include: the coupling of climate change scenarios and weather-based disease forecasting, pest and disease distributions models, pathogen effects on plant diversity (e.g. analysis of adaptation measures) and modified habitats (e.g. presence of new grass species and antagonist species of pathogens).

2.4. Embedment of the carry-over effect

A "carryover effect" is an effect which leads from one condition of the system to another. This effect is usually related to clustering events together in time. This effect has been poorly investigated within models. However, it may play a key role in agricultural modelling in the event in which performing or not in one condition can affect the performance of the system in another condition. Under a specific condition represented by a given model parametrization, the intensity of an event can temporarily increase or decrease after the occurrence of the same event. Despite the importance of this effect for understanding the trajectories of physiological mechanisms and variations in the variables of interest, the integration of this effect into agricultural models is complex and hard to set. Following the definition proposed by O'Connor et al. (2014), in an ecological context, *"carryover effects occur in any situation in which an individual's previous history and experience explains their current performance in a given situation"* and the term performance is *"a broad term that encompasses the action or process of performing a function, and can occur over a range of different time-scales"*.

Based on this definition, linking a specific condition to a previous effect within an agricultural model is not trivial because it requires that all hydrological, biological, pedological and chemical-physical processes are defined.

The main carryover effect considered within crop models usually concerns the effect of previous crops or inter-crop measures. More specifically, it accounts for soil water-related effects along with the carry-over of carbon and nitrogen in below and above ground crop residues (Reckling et al., 2016). This type of approach is usually static with stationary states over the following rotation cycles. A few models also accounts for quality and characteristics of crop residues (Rahn et al., 2010) or the effects of legumes on other crop species.

Currently, one of the main needs for agricultural models is the improvement of carryover effects in relation to soil-plant atmosphere emissions. This is a crucial point in the modelling discussion since the understanding of how previous management (e.g. crop type, agricultural practices, livestock density.) can affect the GHG emissions from the current situation may result a key point for climate change mitigation.

3. Description of the missing processes: Livestock models

In the perspective of an increase in the world population by approaching the end of the century, an efficient food production is expected to be more and more needed. In this context, the increasing consumption of animal protein appears to be necessary, especially in undeveloped countries, where the health benefits of eating modest amounts of meat can overcome the less availability of cereals which, by contrast, are used for feeding animals (Eisler et al., 2014).

However, livestock systems are currently hit by several issues which contribute to decrease the final production in several areas of the world. Among them there are: reduction in land availability (e.g. owing to urbanization and biofuel production), lack of water, soil degradation and climate change (Eisler et al., 2014). This latter, however, is likely the most troubling since it is expected not only to directly affect yield quantity and quality due to changed climatic conditions, but also to indirectly impact the livestock sector through attacks of pest and disease on animals and their feeds (Kipling et al., 2016).

3.1. Pathogens and disease

Knowing in advance the pathogens dynamics can help finding reasonable and efficient solutions for reducing the future negative impacts of pathogens on livestock production systems. In this context, modelling the risks associated with future diseases may be a smart perspective. As reported by Fox et al. (2012), however, given the complexity of the topic just a few predictions are currently available.

As highlighted in a modelling review by Kipling et al., (2016), several predictions were currently offered by correlative models. Despite these tools have already provided projections of future risk for livestock pathogens (see Tatem et al., 2003 and Fox et al., 2011 for Blue Tongue Virus and liver fluke, respectively), they showed some limitations mainly due to lack of dynamic processes, based on specific ecological niches and their current habitats (Elith and Leathwick, 2009; Heikkinen et al., 2006; Fox et al., 2012; Pagel and Schurr, 2012).

These limitations could be overcome using process-based models, which allow an approach based on a deeper knowledge of the physiology of hosts and pathogens, and their response to environmental variables (Robertson et al., 2003). These models may result highly efficient if parametrized for future climate conditions and taking into account parameters to characterize specific pathogens and farming systems, livestock managements, physiological thresholds of pathogens and methods for their controlling as well as of the occurred diseases. Whilst process-based models are widely developed and applied in other topics (i.e. crop and grassland models), progress in livestock modelling still remains limited. This is primarily due to the scarcity of data concerning pathogens activity and their physiological responses to climate variables. More specifically, whilst enough information on the relation between pathogens and thermal variables can be found, very scarce are those related to the response to other climate variables which are expected to change (i.e. rainfall, UV, ozone and drought).

3.2. Heat stress

Harsh climate conditions can cause in animals a reflex reaction to stress. The type of stress depends on the environmental conditions experienced by animals and can cause consequences which vary from discomfort to death (Das et al., 2016). Various types of stress are detrimental for health of various animal species but, within livestock production systems, welfare may be seriously compromised by heat stress. Cattle and sheep cannot vary in a wide range their body temperatures since they balance heat loss or gain, and heat production (Cabanac, 1975; Mount, 1979; Crawshaw, 1980). Increasing heat conditions leads to an evolution of physiological processes which start from sensible heat loss until to the recruitment of evaporative processes, primarily sweating and increased respiratory rate (Mortola and Frappell, 2000). When severe heat stress is present, detrimental effects on productivity, growth, development (Collier and Gebremedhin, 2015) and reproduction (de Rensis et al., 2015) of animals can be observed.

In this context, the expected climate change may further increase this type of stress in livestock production systems due to the expected general increase in thermal variables. For instance, in Southern Europe and the Mediterranean, heatwaves and droughts are expected to become more frequent (Lenderink and Van Meijgaard, 2008) whit increases in warm temperature extremes including events such as hot days (Tmax > 30 °C) and tropical nights (Tmin > 20°C) (Giannakopoulos et al., 2009; Tolika et al., 2009).

Among the measurements for assessing heat stress in cattle, respiratory rate, character and body temperature elevation are the most commonly used measures. However, these are usually not easily measurable under field conditions where the number of animals is high (Mader et al., 2006). Since 1990s one of the mostly used measurements for exploring the cattle health is the Temperature Humidity Index (THI). This is a bioclimatic index which considers the joint effects of environmental temperature and relative humidity. Despite this index is useful and easy to apply to assess the risk of heat stress, it shows some important limitations. For instance, the index does not include the effect of weather variables such as solar radiation, wind speed, and duration of exposure. Moreover, different animals can have different responses to the same thermal stress level (Gaughan et al., 2012).

The majority of the models developed for assessing the impact of heat stress on livestock production systems are empirical and concern the relation between increases in THI above calculated thresholds and the variables of interests (i.e. mortality, quality, specific chemical compounds) (Gorniak et al., 2014; Bertocchi et al., 2014; Morignat et al., 2015; Hill and Wall, 2015). As usual when empirical models are applied, limitations due to the reduced range of incorporated factors in describing the whole process are present. For instance, as suggested by some studies (Bernabucci et al., 2010; Nardone et al., 2010), factors impacting livestock responses to thermal indices are often missing, which include geographic location, genotype, age, physiological and productive phase, acclimation state and management.

Currently, only a few process-based models for livestock systems have been developed (see Mitchell, 2006; Thompson et al., 2014). The ability of these tools to cope with future issues in livestock systems require further improvements. In this context, processes related to physical (thermal balances, heat stress) and physiological aspects (productivity and growth) should be improved by considering individual responses or effects on water requirements (Howden and Turnpenny, 1998). Also, these processes should be integrated and combined with models able to simulate management, providing information related to efficient adaptation options for reducing heat stress impacts (Lacetera et al., 2013). These tools operating at wider scale may be fundamental for gaining inclusive data on the economic consequences of climate change impacts on livestock systems production.

3.3. Grassland productivity and nutritional value

Grassland productivity depends on several factors which vary from climatic variables such as temperature and water stress (Knapp et al., 2001) to type of management, and can be further expanded by considering the intrinsic genetic characteristics of pasture plant species. When plant communities and management are the same, climate is the main driver inter-annual and seasonal changes in productivity. In this perspective, climate change is expected to lead to strong modifications in grassland productivity across several European regions. The expected strongest warming, in Southern Europe in summer and in Northern Europe in winter (Kjellström et al., 2011), joint with a general precipitation increase in Northern Europe and decrease in Southern Europe (Kjellström et al., 2011), may extend the growing seasons in the north (Höglind et al., 2013) and increase the risk of drought in Mediterranean regions (van Oijen et al., 2014).

In the last years several models simulating grassland systems have been developed (Bellocchi et al., 2013). These models range from grassland-specific models to multi-system approaches (Perego et al., 2013; Ma et al., 2015; Coucheney et al., 2015) and are mainly characterized by monospecific swards or simple mixtures (Lazzarotto et al., 2009).

Despite these tools provide interesting and often reliable information, several needs are still unmet. Among these, the modelling of plant communities beyond simple mixtures (Duru et al., 2009), the integrated effect of climate and management on the nutritive value of grassland species, dynamic processes able to reproduce the grassland species adaptation to changing conditions, run-off of phosphorous and its interaction with climate and management (Benskin et al., 2014), soil-water components and impact of grazing on erosion (Bénié et al., 2005).

Implementing these processes within grassland models may provide reliable outcomes which may be used by policymakers in order to support policy choices for improving livestock production systems in a changed climate.

3.4. GHG emissions

Simulation models can be suitable tools for the construction of emission inventories, and for facilitating analyses of emissions from complex contexts. Modelling tools are available, which consider the main processes underlying agricultural GHG emissions. This is specifically an issue for livestock production systems, where CH_4, NO_3, NH_3 and N_2O emissions are from enteric fermentation, manure management, animal housing, and grassland soils (Gerber et al., 2013).

Among the several agricultural compartments, livestock production systems play a fundamental role in CH_4 emissions. Models are available incorporating the effect of factors such as type and quantity of organic matter in the manure, and manure storage type duration and temperature (Li et al., 2012; Sommer et al., 2009). However, important processes such as anaerobic slurry digestion, the impact of heat stress and animal diseases or the leakage of CH_4 are still lacking. These processes are especially relevant at farm-scale level. Implementing these processes into mechanistic models may help finding new ways for reducing CH_4 and other GHG emissions, in turn contributing to climate change mitigation.

Also NH_3 is a great source of GHG from livestock production systems mainly due to manure management. NH_3 emissions are forced and affected by changes in climate conditions. Whilst the latter were recently considered by Rotz et al. (2014), which investigated how NH_3 emissions are sensitive to climate conditions, the modelling of the effect of food type and quality on NH_3 emissions for grazed animals still remains a challenge.

Several mechanistic models are already available for assessing N_2O emissions from manure and soil (Li et al., 2012) or from leaching of N compounds from pastures. Some aspects, however, should be improved. Among these, we indicate parametrization and prediction of oxygen deficit in soil, the effect of different management options on N dynamics and, overall, the joint effect with soil characteristics and climate. Overall, there is a need to further improve GHG dynamics from grassland-livestock systems. Improved models would support analyses at farm and national scales to better cope with climate change and enhance already existent adaptation and mitigation strategies.

4. Conclusions

At present, process-based biogeochemical models represent a valuable tool for examining the impacts of climate change in agriculture and cope with the consequences of altered weather patterns. Regardless the presence of several divergences between models at simulating crop and grassland-livestock production systems due to a different interpretation of physical and biogeochemical processes, some approaches still need to be further improved to facilitate the operational use of these tools over these areas.

In this report several of these missing approaches were reported. Among these we suggested for crop/grassland systems the implementation of the effects of climate extremes on biological systems, the modelling of multi-species sward, the coupling of pest and disease sub-models and the improvement of the carry-over effect. For grassland-livestock production systems we mainly indicated as the approaches to be implemented the impacts and dynamics of pathogens and disease, the heat stress effects on livestock, the effects on grassland productivity and nutritional values and the improvement of GHG emissions dynamics.

The great effort required for implementing these missing approaches would mainly due to the extension of the existing body of knowledge on ecological and biogeochemical concepts. At the same time, however, the possibility to implement these approaches could likely improve the representation of the dynamics of processes of crop and grassland-livestock systems, thus providing considerable advantages for stakeholders.

References

Angulo, C., Rötter, R., Trnka, M., Pirttioja, N., Gaiser, T., Hlavinka, P., Ewert, F., 2013. Characteristic ‘fingerprints’ of crop model responses to weather input data at different spatial resolutions. Eur. J. Agron. 49, 104-114. http://dx.doi.org/10.1016/j.eja.2013.04.003

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Muller, C., Kumar, S.N., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stockle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3, 827-832. http://dx.doi.org/10.1038/nclimate1916

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Glob. Change Biol. 17, 997-1012. http://dx.doi.org/10.1111/j.1365-2486.2010.02262.x

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., Whittaker, J.B.,2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Glob. Change Biol. 8, 1-16. http://dx.doi.org/10.1046/j.1365-2486.2002.00451.x

Baumann, D.T., Bastiaans, L., Goudriaan, J., van Laar, H.H., Kropff, M.J., 2002. Analysing crop yield and plant quality in an intercropping system using an eco-physiological model for interplant competition. Agric. Syst. 73, 173-203. http://dx.doi.org/10.1016/S0308-521X(01)00084-1

Bellocchi, G., Ma, S., Köchy, M., Braunmiller, K., 2013. Identified grassland-livestock production systems and related models. FACCE MACSUR Reports 2, D-L2.1.1.

Bénié, G.B., Goïta, K., Kabore, S.S., Courel, M.F., 2005. Remote sensing-based spatio-temporal modeling to predict biomass in Sahelian grazing ecosystem. Ecol. Model. 184, 341–354. http://dx.doi.org/10.1016/j.ecolmodel.2004.10.012

Benskin, C.M.H., Roberts, W.M., Wang, Y., Haygarth, P.M., 2014. Review of the annual phosphorus loss estimator tool – a new model for estimating phosphorus losses at the field scale. Soil Use Manag. 30, 337–341. http://dx.doi.org/10.1111/sum.12128

Bernabucci, U., Lacetera, N., Baumgard, L.H., Rhoads, R.P., Ronchi, B., Nardone, A., 2010. Metabolic and hormonal acclimation to heat stress in domesticated ruminants. Animal 4, 1167–1183. http://dx.doi.org/10.1017/s175173111000090x

Bertocchi, L., Vitali, A., Lacetera, N., Nardone, A., Varisco, G., Bernabucci, U., 2014. Seasonal variations in the composition of Holstein cow's milk and temperature-humidity index relationship. Animal 8, 667–674. http://dx.doi.org/10.1017/s1751731114000032

Boote, K.J., Jones, J.W., White, J.W., Asseng, S., Lizaso, J.I., 2013. Putting mechanisms into crop production models. Plant Cell Environ. 36, 1658e-1672. http://dx.doi.org/10.1111/pce.12119

Cabanac, M., 1975. Temperature regulation. Ann. Rev. Phys. 37, 415–439. http://dx.doi.org/10.1146/annurev.ph.37.030175.002215

Challinor, A.J., Wheeler, T., Craufurd, P., Slingo, J., 2005. Simulation of the impact of high temperature stress on annual crop yields. Agric. For. Meteorol. 135, 180-189. http://dx.doi.org/10.1016/j.agrformet.2005.11.015

Challinor, A.J., Ewert, F., Arnold, S., Simelton, E., Fraser, E., 2009. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. J. Exp. Bot. 60, 2775-2789.http://dx.doi.org/0.1093/jxb/erp062

Chaparro, M.A.E., Canziani, G.A., Saumell, C.A., Fiel, C.A., 2011. Estimation of pasture infectivity according to weather conditions through a fuzzy parametrized model for the free-living stage of Ostertagia ostertagi. Ecol. Model. 222, 1820–1832. http://dx.doi.org/10.1016/j.ecolmodel.2011.03.019

Collier, R.J., Gebremedhin, K.G., 2015. Thermal biology of domestic animals. Annu. Rev. Anim. Biosci. 3, 513–532. http://dx.doi.org/10.1146/annurev-animal-022114-110659

Confalonieri, R., 2014. CoSMo: A simple approach for reproducing plant community dynamics using a single instance of generic crop simulators. Ecol. Model. 286, 1-10. doi: 10.1016/j.ecolmodel.2014.04.019

Corre-Hellou, G., Faure, M., Launay, M., Brisson, N., Crozat, Y., 2009. Adaptation of the STICS intercrop model to simulate crop growth and N accumulation in pea-barley intercrops. Field Crop. Res. 113, 72-81. http://dx.doi.org/10.1016/j.fcr.2009.04.007

Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., García de Cortázar-Atauri, I., Ripoche, D., Beaudoin, N., Ruget, F., Andrianarisoa, K.S., Le Bas, C., Justes, E., Léonard, J., 2015. Accuracy, robustness and behavior of the STICS soil–crop model for plant, water and nitrogen outputs: evaluation over a wide range of agro-environmental conditions in France. Environ. Model. Softw. 64, 177–190. http://dx.doi.org/10.1016/j.envsoft.2014.11.024

Crawshaw, L.J., 1980. Temperature regulation in vertebrates. Ann. Rev. Phys. 42, 473–491. http://dx.doi.org/10.1146/annurev.ph.42.030180.002353

Dahlman, R.G., 1985. Modeling needs for predicting responses to CO_2 enrichment: plants, communities and ecosystems. Ecol. Mod. 29, 77-106. http://dx.doi.org/10.1016/0304-3800(85)90048-1

Das, R., Sailo, L., Verma, N., Bharti, P., & Saikia, J., 2016. Impact of heat stress on health and performance of dairy animals: A review. Vet. World 9, 260-268. http://dx.doi.org/10.14202/vetworld.2016.260-268

de Rensis, F., Garcia-Ispierto, I., López-Gatius, F., 2015. Seasonal heat stress: clinical implications and hormone treatments for the fertility of dairy cows.

Theriogenology 84, 659–666. http://dx.doi.org/10.1016/j.theriogenology.2015.04.021

Donatelli, M., Van Ittersum, M., Bindi, M., Porter, J., 2002. Modelling cropping systems-highlights of the symposium and preface to the special issues. Eur. J. Agron. 18, 1-11. http://dx.doi.org/ 10.1016/S1161-0301(02)00095-3

Duru, M., Adam, M., Cruz, P., Martin, G., Ansquer, P., Ducouytieux, C., Jouany, C., Theau, J.P., Viegas, J., 2009. Modelling above-ground herbage mass for a wide range of grassland community types. Ecol. Model. 220, 209–225. http://dx.doi.org/10.1016/j.ecolmodel.2008.09.015

Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J., Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V.K., van Saun, R., Winter, M., 2014. Agriculture: steps to sustainable livestock. Nature 507, 32–34. http://dx.doi.org/10.1038/507032a

Eitzinger, J., Thaler, S., Schmid, E., Strauss, F., Ferrise, R., Moriondo, M., Bindi, M., Palosuo, T., R€otter, R., Kersebaum, K.C., Olesen, J.E., Patil, R.H., S¸ Aylan, L., Çaldag, B., Çaylak, O., 2013. Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. J. Agric. Sci. 151, 813-835. http://dx.doi.org/10.1017/S0021859612000779

Elith, J., Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. Annu. Rev. Ecol. Evol. Syst. 40, 677–697. http://dx.doi.org/10.1146/annurev.ecolsys.110308.120159

Ewert, F., van Ittersum, M.K., Heckelei, T., Therond, O., Bezlepkina, I., Andersen, E., 2011. Scale changes and model linking methods for integrated assessment of agri-environmental systems. Eur. J. Agron. 142, 6-17. http://dx.doi.org/10.1016/j.agee.2011.05.016

Fox, N.J., Marion, G., Davidson, R.S., White, P.C.L., Hutchings, M.R., 2012. Livestock helminths in a changing climate: approaches and restrictions to meaningful predictions. Animals 2, 93-107. http://dx.doi.org/10.3390/ani2010093

Fox, N.J., White, P.C.L., McClean, C.J., Marion, G., Evans, A., Hutchings, M.R., 2011. Predicting impacts of climate change on *Fasciola hepatica* risk. PLoS ONE 6, e16126. http://dx.doi.org/10.1371/journal.pone.0016126

Gaughan, J.B., Mader, T.L., Gebremedhin, K.G., 2012. Rethinking heat index tools for livestock. In: Collier, R.J., Collier, J.L. (Eds.), Env. Phys. livestock. Wiley-Blackwell, Chichester, 243–265. http://dx.doi.org/10.1002/9781119949091.ch14

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. FAO, Rome.

Giannakopoulos, C., Le Sager, P., Bindi, M., Moriondo, M., Kostopoulou, A. Goodess, C.M., 2009. Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. Global Planet. Change 68, 209-224. http://dx.doi.org/10.1016/j.gloplacha.2009.06.001

Gorniak, T., Meyer, U., Südekum, K.-H., Dänicke, S., 2014. Impact of mild heat stress on dry matter intake, milk yield and milk composition in mid-lactation Holstein dairy cows in a temperate climate. Arch. Anim. Nutr. 68, 358–369. http://dx.doi.org/10.1080/1745039x.2014.950451

Hansen, J., M. Sato, M., R. Ruedy, R., 2012. Perception of climate change. Proc. Natl. Acad. Sci. U.S.A., 109, E2415. doi: 10.1073/pnas.1205276109

Hanson, C E., Palutikof, J.P., Livermore, M. T., Barring, L., Bindi, M., Corte-Real, Durao, R., Giannakopoulos, C., Good, P., Holt, T., Kundzewicz, Z., Leckebusch, G.C., Moriondo, M., Radziejewski, M., Santos, J., Schlyter, P., Schwarb, M., Stjernquist, I., Ulbrich, U.J., 2007. Modelling the impact of climate extremes: an overview of the MICE project. Clim. Chang. 81, 163-177. http://dx.doi.org/10.1007/s10584-006-9230-3

Heikkinen, R.K., Luoto, M., Araújo, M.B., Virkkala, R., Thuiller, W., Sykes, M.T., 2006. Methods and uncertainties in bioclimatic envelope modelling under climate change. Prog. Phys. Geogr. 30, 751–777. http://dx.doi.org/10.1177/0309133306071957

Hill, D.L., Wall, E., 2015. Dairy cattle in a temperate climate: the effects of weather on milk yield and composition depend on management. Animal 9, 138–149. http://dx.doi.org/10.1017/S1751731114002456

Höglind, M., Thorsen, S.M., Semenov, M.A., 2013. Assessing uncertainties in impact of climate change on grass production in northern Europe using ensembles of global climate models. Agric. For. Meteorol. 170, 103–113. http://dx.doi.org/10.1016/j.agrformet.2012.02.010

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104, 19691-19696. http://dx.doi.org/10.1073/pnas.0701890104.

Howden, S.M., Turnpenny, J., 1998. Working document 98/03: Modelling heat stress and water loss of beef cattle in subtropical Queensland under current climates and climate change. CSIRO Wildlife and Ecology, Lyneham, Australia.

Jamieson, M.A., Trowbridge, A.M., Raffa, K.F., Lindroth, R.L., 2012. Consequences of climate warming and altered precipitation patterns for plant-insect and multitrophic interactions. Plant Physiol. 160, 1719-1727. http://dx.doi.org/10.1104/pp.112.206524

Kipling, R. P., Bannink, A., Bellocchi, G., Dalgaard, T., Fox, N. J., Hutchings, N. J.,Kjeldsen, C., Lacetera, N. , Sinabell, F., Topp, C.F.E., van Oijen, M., Virkajärvi, P., Scollan, N.D., 2016. Modeling European ruminant production systems: facing the challenges of climate change. Agric. Syst. 147, 24-37. http://dx.doi.org/10.1016/j.agsy.2016.05.007

Kjellström E., Nikulin G., Hansson U., Strandberg G., Ullerstig A., 2011. 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Tellus, Series A: Dynamic Meteorology and Oceanography 63, 24-40. http://dx.doi.org/10.1111/j.1600-0870.2010.00475.x

Knapp, A.K., Briggs, J.M., Koelliker, J.K., 2001. Frequency and extent of water limitation to primary production in a mesic temperate grassland. Ecosys. 4, 19-28. http://dx.doi.org/10.1007/s100210000057

Lacetera, N., Segnalini, M., Bernabucci, U., Ronchi, B., Vitali, A., Tran, A., Guis, H., Caminade, C., Calvete, C., Morse, A., Baylis, M., Nardone, A., 2013. Climate induced effects on livestock population and productivity in the Mediterranean area. In: Navarra, A., Tubiana, L. (Eds.), Regional assessment of climate change in the Mediterranean. Springer, Netherlands, pp. 135–156. ISBN 978-94-007-5772-1

Lazzarotto, P., Calanca, P., Fuhrer, J., 2009. Dynamics of grass-clover mixtures-an analysis of the response to management with the PROductive GRASsland Simulator (PROGRASS). Ecol. Model. 220, 703–724. http://dx.doi.org/10.1016/j.ecolmodel.2008.11.023

Lenderink, G., van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. Nat. Geosci. 1, 511-514. http://dx.doi.org/10.1038/ngeo262

Li, C., Salas,W., Zhang, R., Krauter, C., Rotz, A., Mitloehner, F., 2012. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosyst. 93, 163–200. http://dx.doi.org/10.1007/s10705-012-9507-z

Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Change 3, 497-501. http://dx.doi.org/10.1038/nclimate1832

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333, 616-620. http://dx.doi.org/10.1126/science.1204531

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M., Peyraud, J.L., 2014. Potential of legume- based grassland–livestock systems in Europe: a review. Grass Forage Sci. 69, 206–228. http://dx.doi.org/10.1111/gfs.12124

Ma, S., Lardy, R., Graux, A.-I., B.T., H., Klumpp, K., Martin, R., Bellocchi, G., 2015. Regional scale analysis of carbon and water cycles on managed grassland systems. Environ. Model. Softw. 72, 356-371. http://dx.doi.org/10.1016/j.envsoft.2015.03.007

Mader, T.L., Davis, M.S., Brown-Brandl, T., 2006. Environmental factors influencing heat stress in feedlot cattle. Journal of Animal Science 84, 712–719. doi: 10.2527/2006.843712x

Maiorano, A., Cerrani, I., Fumagalli, D., Donatelli, M., 2014. New biological model to manage the impact of climate warming on maize corn borers. Agron. Sustain. Dev. 34, 609–621. doi:10.1007/s13593-013-0185-2

Maire, V., Soussana, J.-F., Gross, N., Bachelet, B., Pagès, L., Martin, R., Reinhold, T., Wirth, C., Hill, D., 2013. Plasticity of plant form and function sustains productivity and dominance along environment and competition gradients. A modelling experiment with GEMINI. Ecol. Model. 254, 80-91. http://dx.doi.org/10.1016/j.ecolmodel.2012.03.039

Mitchell, M.A., 2006. Using physiological models to define environmental control strategies. In: Gous, R., Fisher, C., Morris, T.R. (Eds.), Mechanistic modelling in pig and poultry production. CAB International, Wallingford, Oxford, pp. 209–228.

Morignat, E., Gay, E., Vinard, J.-L., Calavas, D., Hénaux, V., 2015. Quantifying the influence of ambient temperature on dairy and beef cattle mortality in France from a time-series analysis. Environ. Res. 140, 524–534. http://dx.doi.org/10.1016/j.envres.2015.05.001

Moriondo, M., Bindi, M., Kundzewicz, Z.W., Szwed, M., Chorynski, A., Matczak, P., Radziejewski, M., McEvoy, D., Wreford, A., 2010. Impact and adaptation opportunities for European agriculture in response to climatic change and variability. Mitig. Adapt. Strateg. Glob. Change 15, 657-679. http://dx.doi.org/10.1007/s11027-010-9219-0

Moriondo, M., Giannakopoulos, C., Bindi, M., 2011. Climate change impact assessment: the role of climate extremes in crop yield simulation. Clim. Change 104, 679-701. http://dx.doi.org/10.1007/s10584-010-9871-0

Mortola, J.P., Frappell, P.B., 2000. Ventilatory responses to changes in temperature in mammals and other vertebrates. Ann. Rev. Phys. 62, 847–874. http://dx.doi.org/10.1146/annurev.physiol.62.1.847

Mount, L.E., 1979. Adaptation to thermal environment: man and his production animals. Edward Arnold, London, UK. ISBN 0713127406

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M.S., Bernabucci, U., 2010. Effects of climate changes on animal production and sustainability of livestock systems. Livest. Sci. 130, 57–69. http://dx.doi.org/10.1016/j.livsci.2010.02.011

O'Connor, C.M., D.R. Norris, D.R., Crossin, G.T., Cooke, S.J., 2014. Biological carryover effects: linking common concepts and mechanisms in ecology and evolution. Ecosphere 5, 28. http://dx.doi.org/10.1890/ES13-00388.1

O'Connor, L.J., Walkden-Brown, S.W., Kahn, L.P., 2006. Ecology of the free-living stages of major trichostrongylid parasites of sheep. Vet. Parasitol. 142, 1–15. http://dx.doi.org/10.1016/j.vetpar.2006.08.035

Pagel, J., Schurr, F.M., 2012. Forecasting species ranges by statistical estimation of ecological niches and spatial population dynamics. Glob. Ecol. Biogeogr. 21, 293–304. http://dx.doi.org/10.1111/j.1466-8238.2011.00663.x

Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Patil, R.H., Ruget, F., Rumbaur, C., Takáč, J., Trnka, M., Bindi, M., Çaldağ, B., Ewert, F., Ferrise, F., Mirschel, W., Şaylan, L., Šiška, B., Rötter, R., 2011. Simulation of winter wheat yield and its variability in different climates of Europe: a comparison of eight crop growth models. Eur. J. Agron. 35, 103-114. http://dx.doi.org/10.1016/j.eja.2011.05.001

Perego, A., Giussani, A., Sanna, M., Fumagalli, M., Carozzi, M., Alfieri, L., Brenna, S., Acutis, M., 2013. The ARMOSA simulation crop model: overall features, calibration and validation results. Ital. J. Agrometeorol. 18, 23–38.

Rahn, C.R., K. Zhang, R. Lillywhite, C. Ramos, J. Doltra, J.M. de Paz, H. Riley, M. Fink, C. Nendel, K. Thorup-Kristensen, A. Pedersen, F. Piro, A. Venezia, C. Firth, U. Schmutz, F. Rayns, K. Strohmeyer, 2010. Eu-Rotate_N - a decision support system - to predict environmental and economic consequences of the management of nitrogen fertilizer in crop rotations. Eur. J. Hortic. Sci. 75, 20–32. ISSN 1611-4426

Reckling, M., Hecker, J.M., Bergkvist,G., Watson, C.A., Zander, P., Schläfke, N., Stoddard, F.L., Eory, V., Topp, C.F.E., Maire, J., Bachinger, J., 2016. A cropping system assessment framework evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. 76, 186–197. http://dx.doi.org/10.1016/j.eja.2015.11.005

Rivington, M., Matthews, K. B., Bellocchi, G., Buchan, K., 2006. Evaluating uncertainty introduced to process-based simulation model estimates by alternative sources of meteorological data. Agric. Syst. 88, 451-471. http://dx.doi.org/10.1016/j.agsy.2005.07.004

Robertson, M.P., Peter, C.I., Villet,M.H., Ripley, B.S., 2003. Comparing models for predicting species' potential distributions: a case study using correlative and mechanistic predictive modelling techniques. Ecol. Model. 164, 153–167. http://dx.doi.org/10.1016/S0304-3800(03)00028-0

Rötter, R.P., Hohn, J.G., Fronzek, S., 2012a. Projections of climate change impacts on crop production: a global and a Nordic perspective. Acta Agric. Scand. Sect. A Anim. Sci. 62, 166-180. http://dx.doi.org/10.1080/09064702.2013.793735

Rötter, R.P., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindi, M., Ewert, F., Ferrise, R., Hlavinka, P., Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Trnka, M., 2012b. Simulation of spring barley yield in different climatic zones of Northern and Central Europe: a comparison of nine crop models. Field Crop. Res. 133, 23-36. http://dx.doi.org/10.1016/j.fcr.2012.03.016

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43, 1143–1158. http://dx.doi.org/10.2134/jeq2013.04.0121

Schippers, P., Kropff, M.J., 2001. Competition for light and nitrogen among grassland species: a simulation analysis. Funct. Ecol. 15, 155-164. http://www.jstor.org/stable/2656500

Sippel, S., Zscheischler, J., Heimann, M., Otto, F.E.L., Peters, J., M.D. Mahecha, M.D., 2015. Quantifying changes in climate variability and extremes: Pitfalls and their overcoming, Geophys. Res. Lett., 42. doi:10.1002/2015GL066307.

Smith, G.N., Dukes, J.S. 2013. Plant respiration and photosynthesis in global-scale models: incorporating acclimation to temperature and CO_2. Glob. Change Biol. 19, 45–63. http://dx.doi.10.1111/j.1365-2486.2012.02797.x

Sommer, S.G., Olesen, J.E., Petersen, S.O., Weisbjerg, M.R., Valli, L., Rodhe, L., Béline, F., 2009. Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. Glob. Chang. Biol. 15, 2825–2837. http://dx.doi.org/10.1111/j.1365-2486.2009.01888.x

Soussana, J.-F., Maire, V., Gross, N., Bachelet, B., Pagès, L., Martin, R., Hill, D., Wirth, C., 2012. GEMINI: a grassland model simulating the role of plant traits for com-munity dynamics and ecosystem functioning. Parameterization and evaluation. Ecol. Model. 231, 134-145. doi: 10.1016/j.ecolmodel.2012.02.002

Stromberg, B.E., 1997. Environmental factors influencing transmission. Vet. Parasitol. 72, 247–264. http://dx.doi.org/10.1016/S0304-4017(97)00100-3

Suter, M., Connolly, J., Finn, J.A., Loges, R., Kirwan, L., Sebastià, M.-T., Lüscher, A., 2015. Nitrogen yield advantage from grass–legume mixtures is robust over a wide range of legume proportions and environmental conditions. Glob. Chang. Biol. 21, 2424–2438. http://dx.doi.org/10.1111/gcb.12880

Tao, F., Zhang, Z., 2013. Climate change, high-temperature stress, Rice productivity, and water use in Eastern China: a new superensemble-based probabilistic projection. J. Appl. Meteorol. Climatol. 52, 531-551. http://dx.doi.org/10.1175/JAMC-D-12-0100.1

Tatem, A.J., Baylis, M., Mellor, P.S., Purse, B.V., Capela, R., Pena, I., Rogers, D.J., 2003. Prediction of bluetongue vector distribution in Europe and north Africa using satellite imagery. Vet. Microbiol. 97, 13–29. http://dx.doi.org/10.1016/j.vetmic.2003.08.009

Teixeira, E.I., Fischer, G., van Velthuizen, H., Walter, C., Ewert, F., 2013. Global hotspots of heat stress on agricultural crops due to climate change. Agric. For. Meteorol. 170, 206-215. http://dx.doi.org/10.1016/j.agrformet.2011.09.002

Thompson, V.A., Barioni, L.G., Rumsey, T.R., Fadel, J.G., Sainz, R.D., 2014. The development of a dynamic, mechanistic, thermal balance model for *Bos indicus* and Bos taurus. J. Agric. Sci. 152, 464–482. http://dx.doi.org/10.1017/S002185961300049X

Tolika, K., Maheras, P., Tegoulias, I., 2009. Extreme temperatures in Greece during 2007: Could this be a “return to the future”? Geophys. Res. Lett. 36, L10813. http://dx.doi.org/10.1029/2009GL038538

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. Eur. J. Agron. 18, 57-74. http://dx.doi.org/10.1016/S1161-0301(02)00097-7

van Dijk, J., de Louw, M.D.E., Kalis, L.P.A., Morgan, E.R., 2009. Ultraviolet light increases mortality of nematode larvae and can explain patterns of larval availability at pasture. Int. J. Parasitol. 39, 1151–1156. http://dx.doi.org/10.1016/j.ijpara.2009.03.004

van Ittersum, M., Leffelaar, P., van Keulen, H., Kropff, M., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18, 201-234. http://dx.doi.org/10.1016/S1161-0301(02)00106-5

van Oijen, M., Balkovič, J., Beer, C., Cameron, D.R., Ciais, P., Cramer, W., Kato, T., Kuhnert, M., Martin, R., Myneni, R., Rammig, A., Rolinski, S., Soussana, J.F., Thonicke, K., Van der Velde, M., Xu, L., 2014. Impact of droughts on the carbon cycle in European vegetation: a probabilistic risk analysis using six vegetation models. Biogeosciences 11, 6357–6375. http://dx.doi.org/10.5194/bg-11-6357-2014.

White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crop. Res. 124, 357-368. http://dx.doi.org/10.1016/j.fcr.2011.07.001